CRYSTAL SETS TO SIDEBAND

Chapter 10

Variable Frequency Oscillators (VFOs)

Sooner or later you'll become frustrated with being stuck on a few crystal-controlled frequencies. You would like to have a frequency-tuning knob that covers the entire band and not just a couple kilohertz. This sounds simple, but isn't. It's difficult because, without the stability of a crystal, an ordinary RF oscillator will drift hundreds of hertz while you're sending. The fellow you're talking to probably has a modern transceiver with a narrow, stable passband. From his perspective your signal will quickly drift out of his passband. His digital readout may be calibrated to tenths of a Hertz and he will take great delight in telling you about *YOUR PROBLEM.*

Drift is a big deal today

In the old days, like 1950, receiver passbands were usually huge, like 10 or 20 kilohertz. So we could drift quite a distance before our contacts even noticed, let alone could no longer hear us. Besides, everyone drifted a little back then, so it wasn't worth mentioning. In the really old days, like 1930, the signals drifted so much, that hams often tuned their receivers with one hand while they copied down the Morse code with the other.

A stable variable frequency oscillator can replace a crystal oscillator. This Chapter summarizes what I learned in my odyssey through seven VFO prototypes. My early VFOs drifted hundreds of Hz and I got loads of complaints. After I added temperature compensation, I got the instability down to 20 Hz drift per minute. Some stations notice 20 Hz drift and a few even told me about it. Eventually I built a super-regulated power supply for the VFO and got the drift down to about 5 Hz. I suggest you avoid embarrassment and work directly toward 5 Hz. According to the ARRL handbook, +/- 5 Hz is about as stable as you can achieve without phase lock loop technology with quartz crystal reference.

A 5 MHz VFO tuned by a mechanical variable capacitor

In the old days, when hams transmitted a truly stable CW signal, they might receive a signal report of "RST 579X." The "X" meant that the signal was as stable as a quartz crystal. Now that practically everyone uses crystal-controlled, integrated-circuit frequency synthesizers, you will probably never hear any RSTs with an "X." With a homebrew transmitter you're more likely to hear a detailed complaint about your drifting frequency.

I was talking to a brand new local ham on 40 meters CW. We were chatting at a leisurely 5 words per minute. Of course, he was using a wondrous modern transceiver. It took us an hour to communicate very little information. Finally he tired of the strain and called me on the phone. "By the way," he said, "Were you aware that you drifted over 50 Hz during our QSO?" He thought he was informing me of a grievous defect in my rig. Less than 1 Hz per minute? I was delighted that the drift was so low.

The test equipment needed to build a VFO are a precision multimeter for measuring DC voltage down to millivolts and a frequency standard. A super-accurate, modern receiver is OK, but a frequency counter is better for this application. The hardest part about building a stable VFO is following all the detailed instructions on how to do it. If you’re like me, you’ll have trouble believing that all that inconvenient trivia is really necessary. Yes, you can cut a few corners, but the more compromises you make, the more your VFO will drift.

Low frequency VFOs drift less than high frequency VFOs

It’s practical to build a VFO that operates directly on 160 meters (1.8 to 2.0 MHz) or on 80 meters (3.5 to 4.0 MHz). This makes a CW transmitter design simple. For these bands you just amplify the VFO signal directly. For example, if you have a crystal-controlled QRP designed for 80 meters, an 80 meter VFO can be plugged directly into the crystal socket. You might want to attenuate the signal somewhat before directly substituting a crystal. However, the VFO can replace the crystal and allow you to tune all over the band. If you can build a really first rate VFO for 40 meters, that band would also be practical. Unfortunately, for a given level of sophistication and precision, frequency drift is directly proportional to frequency. You will probably find that somewhere above 5 MHz, there is too much instability to keep the drift under 5 Hz per minute. In order to build a low drift VFO for 40 meters or above, a low frequency VFO can be "converted" up to the desired high frequency. Conversion means literally adding the VFO signal to a high frequency crystal oscillator signal and then extracting the sum frequency with a filter. Frequency conversion is covered in Chapter 11.

Considering the size of most HF ham bands, a VFO needs a tuning range of at least 0.5 MHz. The higher the basic frequency of the VFO, the wider the tuning range you can achieve. ARRL handbook VFO projects have various frequencies ranging from 1.75 to 9 MHz. My CW transmitter VFO ranges from 3.5 to 4.0 MHz. My receiver and SSB-transmitter VFOs tune from 5.0 to 5.5 MHz. In retrospect, if I were starting over, I would have built the 5 MHz VFO first, since that frequency turns out to be more versatile. The disadvantage of a 5 MHz VFO is that 60 meters is the only band it can reach directly. All the stations I have ever heard on 60 are SSB. Generating SSB on the same frequency on which you're transmitting requires a phase shift technique that is rarely used today. As of 2012 it is now legal to transmit CW on 60 meters. However, with only 5 discrete frequencies or "channels," it is a difficult band to use, as explained Chapter 17.

JFET transistors

Junction Field Effect Transistors (JFETs) are ideal for building VFOs. Unlike bipolar transistors, the main current from the drain to the source does not pass through any PN junctions. PN junctions change their characteristics with temperature. Therefore, VFOs made from bipolar transistors tend to drift more than JFETs. JFETs work on the same principle as a MOSFET, but the control gate is a P-N junction diode rather than a capacitor. JFETs were explained and used in the VFO oscillator in the direct conversion receiver in Chapter 7A.

THE VFO CIRCUIT

The basic oscillator

In principle the VFO is almost the same as a quartz crystal oscillator. The crystal is electrically equivalent to an L-C resonant circuit. Therefore, to tune a VFO we can use either a **variable capacitor** or a **variable inductor** to change the resonant frequency.

Homebuilt variable inductors

For decades Collins Radio used variable inductors to tune their top-quality HF receivers. My 1950s era Collins receiver has 16 variable inductors. The main tuning is a large cylinder the size of a soup can. The other 15 are in an intricate geared assembly that switches between the 30 one MHz wide bands. The synchronized powdered iron cores are lowered into their air core inductors like control rods in a nuclear reactor. Try building that in your basement!

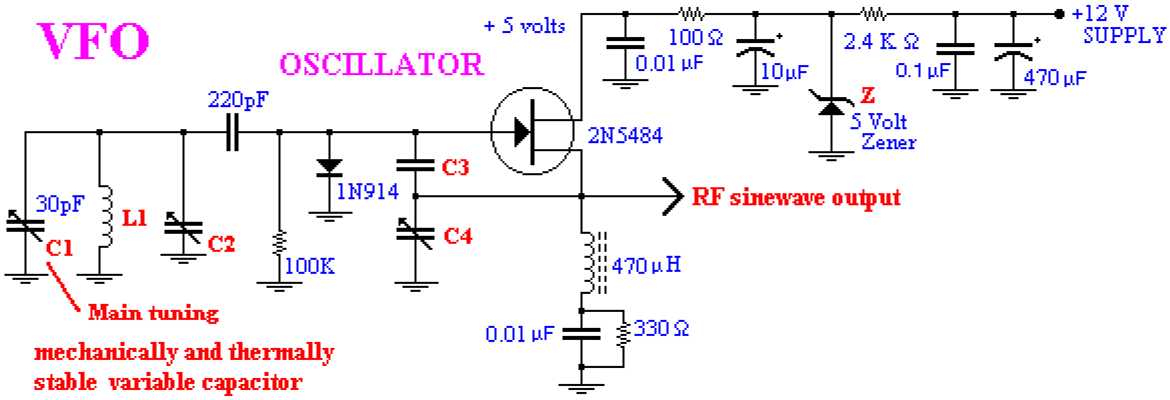
Unfortunately I have never seen hand-tunable inductors for sale. However I have seen two homebrew articles about building receivers tuned with homemade variable inductors. The strategy is to wind a coil on a stiff, hollow, narrow-diameter, plastic coil form. The tuning element consists of a brass screw threaded into the coil form. A knob attached to the screw head is rotated many times to thread the screw in and out of the plastic tube. I was surprised that they used brass rather than threaded powdered iron cores. Brass isn't magnetic, but it acts like a shorted secondary winding on the coil and radically lowers the inductance of the coil. *Any* metal inserted into an air core inductor will change the inductance.

Back when I was a beginning ham, I was blessed to go to a high school that had eight hams enrolled at once. My transmitter back then was a Heathkit DX-20 transmitter tuned by a Heathkit VF-1 VFO. One day I turned on my rig and discovered that the VFO had died. I removed the enclosure and looked inside. The vacuum tubes glowed, but there was no RF output. By dumb luck I happened to glance into the end of the air-core inductor. I discovered that some prankster "friend" of mine had taken my VFO apart and packed wire solder into the bore of the VFO inductor. I removed the solder and revived the VFO. All my alleged friends vigorously denied the sabotage and I never identified the culprit. However, they did smile a lot.

One article I read wound their variable inductor on a soda straw from McDonald's fast food. That doesn't sound rugged, but at least the thin plastic walls tightly couple the coil to a metal screw. ***The biggest challenge to making a variable inductor is mechanical stability.*** When I started my modern VFO projects, I quickly gave up using the powdered iron slug tuned coils that were commonly used in ham gear back the 1960s. Having an adjustable "fixed" inductor for adjusting the tuning range of a variable capacitor would be very helpful. My coils looked stable, but they vibrated and made the signal warble. Another challenge of screw tuning is calibration. The vernier action of a fine threaded screw is wonderful for fine tuning. But with many knob rotations over the full range, calibrating a dial is difficult. A screw-tuned inductor may require an electronic frequency counter.

Variable capacitors

The difficulty of building and calibrating variable inductors probably means that your VFO will use a hand-tunable variable capacitor. It can be similar to the one you used to adjust the crystal frequency in your QRP.



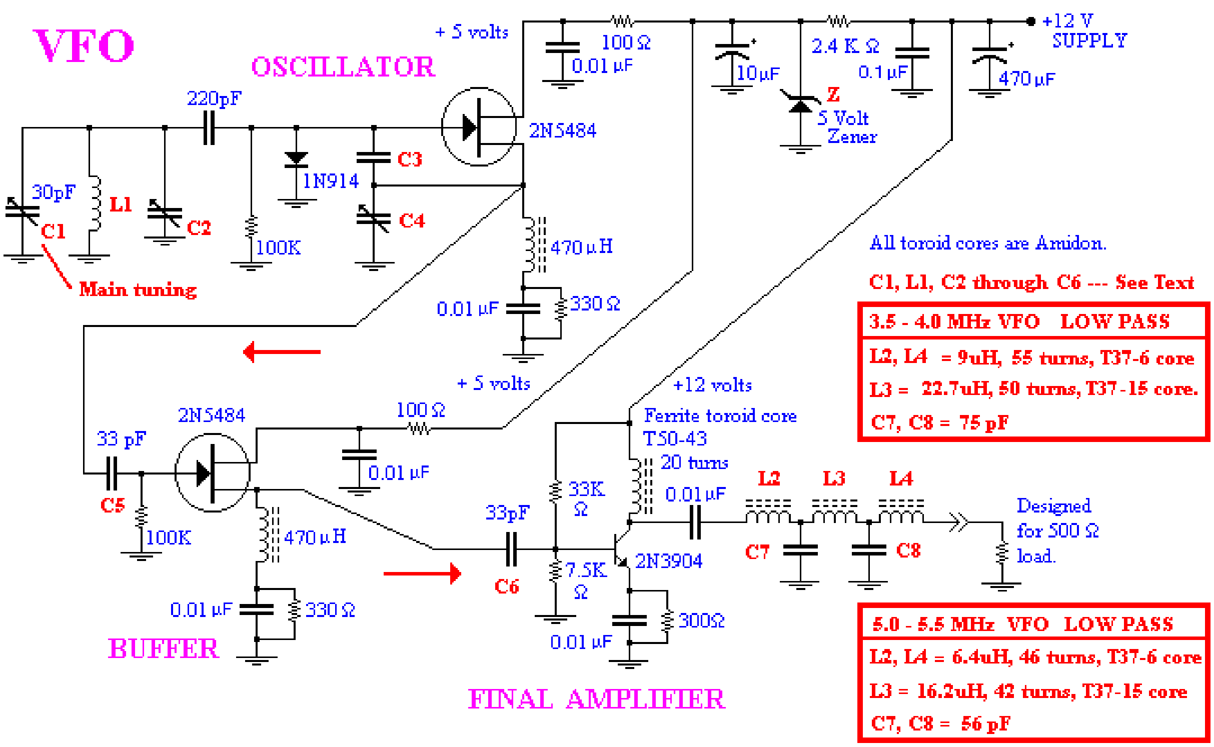
The circuit above is essentially what you will find in your ARRL handbook. It uses a JFET transistor. The oscillator is a ***Colpitts*** and can be recognized by the capacitive divider feedback, C3 and C4. Whenever the source voltage goes up, some of this change is coupled to the gate through C3. This turns the JFET more ON. That is, the feedback is <u>positive</u> which sustains the oscillation. The basic LC resonant circuit that determines the frequency is C1 and L1. C2 is a trimmer capacitor used to adjust the desired tuning range.

So what are the values of C1, L1, C2, etc.? The answer isn't simple. We start with a quality variable capacitor for C1 as described below. For various reasons, **C1 will probably be about 30 pF.** Starting with this capacitor and the need for a 0.5 MHz tuning range, the other values must be determined by trial and error. The values are extremely hard to calculate because C3, C4 and even the 1N914 diode are part of the capacitance. Don't try too hard to get the values right until you have studied this entire chapter and formulated a plan for your VFO. As you will see later, C2, C3 and C4 are part of the temperature compensation strategy and will need to be determined by those considerations first. When you have decided what to do about C3 and C4, then you can work on L1 and C2.

The 470 µHenry choke in the source circuit serves as the load "resistor." That is, the oscillator sinewave output is confined between the operating voltage, +5 volts and ground. Since the sinewave voltage appears across the transistor, the remainder, 5 volts minus the sinewave, must appear across a load of some sort. This choke could be functionally replaced with a resistor, except that a resistor dissipates energy and gets hot. The last thing you need in your VFO is another source of heat. The choke inductance is high enough so that the DC current through it changes very little during one RF cycle and its effect on the frequency of oscillation is minimal and unchanging.

The 1N914 diode on the gate seems counter-productive, but it is used as a clamp to keep the base of the JFET transistor out of the forward conduction region. That is, when the oscillation gets too vigorous and the gate P-N junction begins to turn on at 0.6 volts, the diode will help prevent operation in this range. The VFO as a whole is powered by 12 volts. However, 5 volts derived from a Zener diode regulator (Z) powers the oscillator stage and its buffer. I suggest substituting an LM336-2.5 volt precision Zener diode for the 5 volt ordinary Zener diode. This decreases the output signal voltage, but also reduces the circuit heating to one fourth. Anything that reduces heating increases stability.

The basic VFO circuit



Here is the entire ARRL handbook VFO circuit, but doesn't include the temperature compensation. As you can see, the VFO also contains a buffer stage and a final amplifier. Temperature compensation consists of special circuits that replace either C2 or C4. Any common, small N-channel JFET will work well - J310, MPF102, etc.

Buffer

The buffer stage separates the oscillator from the final amplifier. Otherwise there would be a subtle connection between the load on the VFO output and the oscillator. Believe it or not, without the buffer, if you change the load on the VFO output slightly, the frequency will change too. The buffer is connected to the other stages by C5 and C6. These capacitors should be as small as possible to reduce the connection between the oscillator and final amplifier.

Other connections between the oscillator and output are the power supply line and ground. This is why the supply lines have so many isolation resistors, and electrolytic and ceramic capacitors to ground. All grounds should be securely soldered to the copper ground layer of the printed circuit board. Try to insure that there are no ground paths isolated on long skinny traces that will have tiny voltages across them when current flows.

Final amplifier

The final amplifier raises the VFO output up to the level needed to drive the transmitter. The stage being driven in the transmitter is usually a "mixer" which we shall discuss in Chapter 11. But, if the VFO is designed for the 80 meter ham band, then the next stage after the VFO could be a string of class C amplifiers to increase the output power to the final level. As examples, that might 5 or 50 watts. The VFO final stage will need to deliver at least two volts peak sine wave. Since we have deliberately kept the oscillator and buffer signals tiny, the final amplifier must be a linear or Class A amplifier to get the signal level up to 2 to 5 volts peak. The drive to this transistor is biased with a 33K resistor so that this stage is always turned on.

Low pass filter

The drive to the transmitter should be as pure a sinewave as possible to avoid radiating harmonics outside the hamband. A low pass filter on the output attenuates most of the harmonics above the desired frequency range. A Chebyshev low pass filter is shown designed for a 500 ohm load. In Chapter 6A you were introduced to Chebyshev filters designed for 50 ohms. However, here we have no need for power, just a voltage sinewave. Therefore, the filter is designed for 500 ohms, which is plenty of drive current for this application. Values are given for both a 80 meter VFO (3.5 to 4.0 MHz) or a 5 MHz VFO (5.0 to 5.5 MHz).

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The 50 secrets of avoiding drift

Suppose you were to build the above VFO without reading the details in the following paragraphs: When you first turn it on, you will be disappointed to find that it drifts a hundred Hz per minute or more. ***The drift is caused by temperature change***. The components expand and contract with temperature and this causes small changes in the capacitance and inductance of the components. Air circulating across the board doesn't allow the temperature to stabilize. ***Drift is prevented by preventing temperature change and by choosing components that change as little as possible with temperature.***

VFO building is an art form as arcane as Grandma's secret pie crust recipe or the fine points of building Cub Scout Pinewood Derby racers. As you'll see, there must be 50 ways to improve the drift problem. I have never built a VFO that was completely "stable" and never will. But perhaps that's because I only know the 17 secrets listed below. If you apply as many of these as possible, you should be able to reach the 5 Hz target. It will surely drift less than 20 Hz per minute.

Secret # 1. Use Junction Field Effect Transistors (JFETs). The first secret of a stable VFO is to use a JFET instead of a bipolar transistor. As explained earlier, a field effect transistor is better because it is less sensitive to temperature. I have used 2N3823, 2N5484 and 2N4416 N-channel JFET's for VFO oscillators.

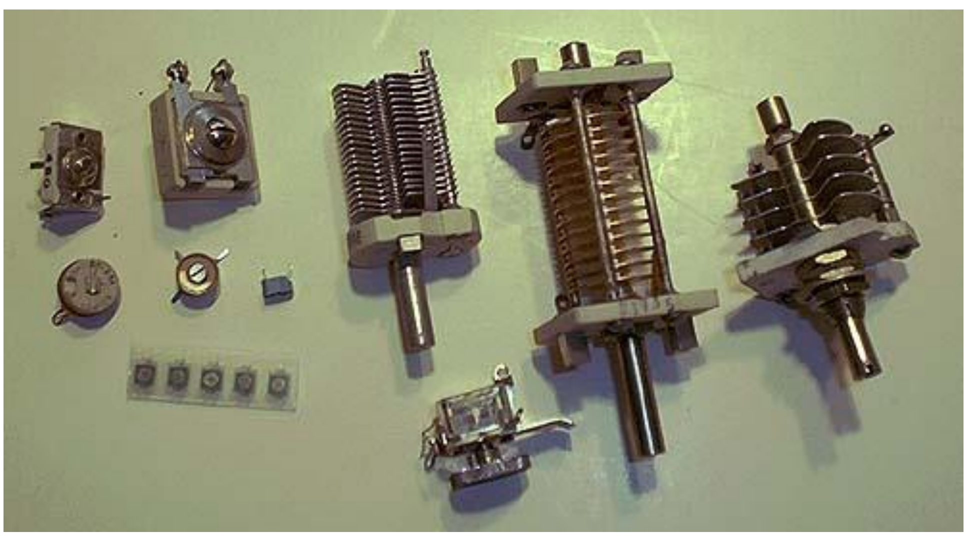
Secret # 2. Seal the VFO in a cast metal box. Simply protecting the VFO from air currents makes a huge improvement. Use a heavy cast metal box so that the temperature will at least change slowly. In contrast, a flimsy sheet-metal aluminum box will heat and cool relatively rapidly. On the other hand, *ANY* box is a huge improvement over not having the circuit isolated from air currents.

Secret # 3. Use single-sided PC board. A double-sided PC board is constructed like a capacitor. That is, thin metal sheets are bonded to a layer of insulator. Unfortunately, the resulting capacitor has a significant temperature coefficient. As temperature increases, the board material expands (thickens) and the capacitance across the board drops. If the VFO is built on traces and islands that have changing capacitance to ground, the frequency of the oscillator will drift slightly.

Secret # 4. Mount the oscillator PC board away from the metal case on standoffs. Following the same principle as above, do not mount the single-sided PC board flush against the metal case. By standing the board up and away from the case, the capacitance between the traces and the metal case can be minimized.

Secret # 5. Choose and mount all components affecting the oscillator LC circuit carefully. All the L and C components in the oscillator should be designed for minimum temperature drift. Referring to the diagram, it is not just capacitors C1 and C2 that affect the frequency. Capacitors in series with the 220 pF capacitor, C3, C4 and even C5 affect the frequency. To at least a tiny degree, ALL components in contact with these capacitances can affect frequency drift. These include the diode, the RF choke, the transistor and even the 100 K resistor.

Secret # 6. Mechanical variable capacitors should be chosen carefully. Although appropriate mechanical variable capacitors are hard to find, they may be the best solution for you. Pick a capacitor of about 30 to 60 PF, but not larger. High capacitance variable capacitors are too sensitive to temperature change. Smaller ones don't tune far enough. ***Don't use a capacitor with aluminum plates*** – they warp too much with temperature. ***Brass is the best metal. Try to find a capacitor with thick, widely-spaced plates.*** Paper-thin plates are compact, but warp too easily.



An assortment of variable caps is shown above. The big brass variable cap just to the right of center is rather big physically. However, out of this group it is the best for a VFO. The capacitor to its right is quite stable, but its capacitance is too small. The tiny green plastic trimmer caps in the clear plastic packaging are positive temperature coefficient variables useful for VFO temperature compensation. The round ceramic white and silver trimmer just above them is my favorite 60 pF trimmer. I used dozens of them in the projects presented in this book. The small variable cap at the bottom center has surprisingly large capacitance, 250 pF. Unfortunately it's too unstable for a VFO.

If the capacitor tuning is linear with degrees of rotation, the frequency it produces will be somewhat non-linear. Ideally, the capacitor plates should have a non-linear shape that allows it to tune an LC resonant circuit so that the frequency will be linear. Rotate a mechanical capacitor through its range and you'll see that a compensated capacitor has rotor plates that are not simple half circles. As they rotate, they do not continuously mesh with the stator plates at the same point. The non-linear correction isn't a big deal, but it is something to be aware of. RF Parts Co. sometimes has adequate capacitors in stock. See www.rfparts.com. As of 2021 their offering of old-style variable caps has become quite limited. Darn! However, they are still the best source I know for leaded transistors, vacuum tubes, coax and other homebuilding parts.

Secret # 7. Varactors are the most stable tuning element. It's hard to buy mechanical variable capacitors that are mechanically and thermally stable. Collins Radio formerly tuned their VFOs with special powdered-iron slug-tuned coils, but I've never seen any for sale. A varactor capacitor controlled by a quality pot can be a good solution to these problems. Varactors are a kind of silicon diode biased with DC voltage. The DC level can be set with a remote potentiometer. A knob on the pot tunes the diode just as you would tune a variable capacitor. In my experience varactors are an order of magnitude more thermally stable than mechanical capacitors. They are at least two orders of magnitude more mechanically stable. You can slap the VFO with your hand and, although other components may vibrate, the varactor will not change its capacitance.

Unfortunately, varactors produce a non-linear scale on the potentiometer frequency tuning knob. This means that the high frequency end of the VFO range will be extremely detailed while the low end may be compressed into a few degrees of rotation. For this to be usable, ideally the potentiometer should be non-linear to compensate. Varactors are discussed in detail below.

Secret # 8. Use C0G fixed capacitors. When selecting fixed capacitors, look for ceramic type C0G (formerly known as NP0). These are supposed to have minimum temperature change. Use these for *ALL* fixed capacitors affecting the LC circuit.

Secret # 9. Use multiple C0G capacitors in parallel to achieve a given value. For example, you might use fixed capacitors for C1 or C2 in the above circuit. For each value needed it is better to use several small ones in parallel rather than one large capacitor. The temperature of a small capacitor stabilizes quickly, whereas heat builds up more slowly in a larger capacitor.

Secret # 10. Temperature compensation for the LC circuit is essential. It took me four prototypes to accept this, but temperature compensation is as important as putting the VFO in a box. Lots of guys claim to have succeeded without it, but I never have. Not using temperature compensation implies that every capacitor and inductance in the VFO must have a zero temperature coefficient. Alternatively, all negative coefficients must be balanced precisely with components that have equivalent positive temperature coefficients. Good luck doing that! Compensation circuits are described below.

Secret # 11. Use an air core inductor or type 7 powdered iron toroid. As usual, it is most convenient to use a powdered iron toroid core. Unfortunately, powdered iron changes its permeability (magnetism factor) with temperature. Therefore, by not using powdered iron, another variable is eliminated. I have successfully used old plastic ball point pen caps as little coil forms for air-core inductors. I bore little holes in the plastic to accept tiny pieces of stiff copper wires to serve as wiring terminals. Unfortunately, a coil made from turns of copper wire on a plastic form will change its dimensions slightly with temperature too. And because an air core inductor requires more turns of wire, there is more opportunity for the copper to change its dimensions, its interwinding capacitance and also its resistance. Sigh. Nothing is perfect.

Among the CWS Bytemark (Amidon) cores, powdered iron type #7 is supposed to have the best thermal stability and my latest VFOs use these. CWS #6 cores have also worked well for me but perhaps #7 is a few percent better. The T50-7 is the same physical size as a T50-6 and its permeability factor is slightly higher. The A_L for T50-7 is 43 versus 40 for the T50-6.

After you have your coil wound and working over the right frequency range, use a drop of epoxy or a mechanical clamp it to fasten it to the board. Without the epoxy, the frequency will warble with the slightest vibration. I once tried to use slug-tuned coils. They were convenient to adjust, but were mechanically and thermally unstable. When I used too much glue to hold my T50-7 core down to the circuit board, the frequency of oscillation dropped and I had to lower C2, C3 or C4 to compensate. A drop of glue is plenty.

Secret # 12. Precision voltage regulation for the VFO supply is vital for precision frequency stability. The 12 volt (or lower) supply voltage for the VFO as whole must be regulated. Ordinary voltage regulators like the LM317 or LM7812 gave me regulation within 0.1 volt. This was OK for frequency stability down to about 20 Hz drift. But to get down to less than 5 Hz, I needed to regulate my VFO power supply to a few millivolts. To achieve this, I built a precision supply that just powers the VFO oscillator and buffer. The less current the supply has to deliver, the more constant its output voltage will be. Precision supply designs are discussed in detail below.

Secret #13. The VFO should draw as little power as possible. The less power drawn, the less heating that occurs inside the VFO box. Also, the less power drawn, the easier it is to build a precision voltage supply to drive the VFO. That is why the VFO was designed for a 500 ohm load rather than 50 ohms like most ham RF circuits. The oscillator and buffer in particular should draw as little current as possible. An external final amplifier stage can boost a tiny sinewave voltage up to whatever voltage you need.

My latest VFOs house the oscillator and buffer inside a cast metal box while the "high power" final stage running on 12 volts is outside the cast metal box so its heat can't affect the oscillator. I ran the oscillator and buffer on just 1 milliampere regulated by a 2.5 volt precision voltage reference Zener.

Secret #14. Every component in the oscillator that dissipates power should be outside the oscillator box. A corollary to designing for low power is moving all the resistors outside the cast metal box. Any component that generates heat is a burden on the oscillator's ability to compensate for the change in temperature. The amplifier that raises the oscillator sinewave voltage to what is needed to drive the mixer does not need to be inside the box. Obviously the temperature compensation system must remain inside the box.

Secret # 15. The precision Zener regulator circuit can partially stabilize frequency. The Zener circuits have an external trim pot that can stabilize the VFO frequency to a significant degree. The Zener data sheet recommends using this trimmer pot to adjust the output voltage to exactly the nominal value, 2.5 volts or 5.0 volts. Instead, use them to adjust for best frequency stability.

Secret #16. If possible, leave the VFO on during transmit. For a receiver VFO, there is no reason why the VFO can't be left running while you are transmitting. When a VFO (or crystal oscillator) is left on continuously, it has time to stabilize and is not constantly heating and cooling. In a receiver, the rest of the circuitry, the IF, the audio, etc., can be turned off with a "mute" signal from the transmitter. The difficulty with leaving a transmitter VFO running during receive is that you will probably hear it in the receiver. This can sometimes be eliminated by enclosing the entire VFO in a tight, grounded metal shield.

I saw a design for a 40 meter QRP transmitter that used an 80 meter VFO, then doubled the frequency to get on 40 meters. Because the basic VFO signal was on 80 meters instead of 40, it was easier for the receiver to filter out the raw 80 meter signal. The VFO could be left on during receive without being audible on the 40 meter band. (Ref. QST magazine, June 2011). Remember that if you simply double or triple a VFO signal, the VFO drift will also be doubled or tripled.

Secret #17. Forget tube oscillators. You old timers may be tempted to use a tube oscillator. I first tried to update an old tube VFO, but tubes get hot and make temperature compensation too difficult. The tube oscillator I was working with used a tiny, low power "Nuvistor." Just before transistors took over, Nuvistors were the latest thing in vacuum tubes. So I was surprised that I couldn't stop the drift. You'll have plenty of trouble without using tubes. You may use bipolar transistors for the final amplifier in your VFO, but not for the oscillator. For good measure you may as well use a JFET for the buffer as well.

Vernier mechanical tuning and frequency indicator

Because a VFO must be tuned precisely to the other fellow's frequency, it is vital to use a vernier tuning gear between the tuning knob and the variable capacitor. In my opinion, the tuning knob should rotate at least three times around for each revolution of the capacitor. More revolutions would be even better. Without vernier tuning, it will be exceedingly difficult to tune your receiver or transmitter accurately to the other fellow's frequency. A planetary reduction gear is generally mounted on the front panel. Machine screws clamp it to the ¼ inch capacitor tuning shaft that protrudes from the VFO box. Geared tuning systems are usually combined with a dial and pointer that you can calibrate. A paper dial can be marked with ink for the calibrations. A plastic cover protects the paper from moisture.

I used a National Company brand vernier dial on one of my VFOs shown at left. Recent interest in QRPs has made these available again after being absent for some years. Look for the ads in ham magazines. Unfortunately, these dials are pretty pricey. For some of my VFOs I used a military surplus reduction gear that had no pointer and dial. I made a pointer out of extra-thin PC board painted black. The dial calibrations were on thin white cardboard covered with 1/8 inch Lucite plastic and screwed onto the front panel.

If you use a varactor variable capacitor as described below, you can use a multi-turn potentiometer for your tuning vernier. This solves the vernier problem, but doesn't offer a way to calibrate the dial. Some hams have built elaborate frequency counters or digital voltmeters as solutions for VFO calibration. All I can say is beware of digital circuitry in your ham equipment. For example, occasionally I have been able to hear digital static in my receiver coming from the Hewlett Packard frequency counter that I use to monitor my transmitter signal. Homebuilt digital circuits (in my experience) always generate radio noise that will interfere with hearing weak signals. Commercial manufacturers make digital technology look easy. So far, all my attempts to build digital circuits using integrated circuits have generated a static "hiss" that I could hear in the receiver. Single chip "PIC" microcontrollers (used in Arduino boards) make a loud static that defies filtering at HF frequencies. If you are using one of those cute little CW keyer kits and it has a PIC microcomputer chip, be sure it can be turned off during receive.

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Varactor Tuning

While building the receiver described in Chapter 13A, I had to construct another VFO. In this prototype I first explored replacing the mechanical tuning capacitor with a varactor. Back-biased P-N junctions block the flow of charge as if they were capacitors. They not only act like capacitors when back-biased, ***they are capacitors***. By biasing them with a DC voltage, say 0 to 10 volts, the capacitance can be tuned like a variable capacitor. As more and more voltage is placed across the diode, the ion contaminants in the semiconductor are used up and the charge it can store is diminished. In other words, PN junction diodes change their capacitance inversely proportional to the voltage on them. ***Varactors are voltage-variable capacitors.***

The MV104 varactor

My favorite varactor has been the Motorola MV104. It is a dual diode that can be used in parallel or series. According to my capacitance meter, it can either produce 120 pF or 60 pF. When the diodes are back biased, the capacitance drops, like a varable capacitor. With just 5 volts DC bias on the diode, the capacitance change is reasonably linear. With more bias voltage, the capacitance changes very little for big voltage changes. The MV104 is extinct, but the similar Siemens BB104 is available for about $1.00 each.

Varactors are specialized P-N junction silicon diodes that were designed just for this purpose. However, I have seen VFO circuits that even use ordinary silicon diodes like the 1N914 or 1N4148 as varactors. Large rectifier diodes like the 2N4001 can have 20 pF or more. Varactor diodes usually have 30 pF or more capacitance. Notice that we can increase the tuning range by using two or more varactors in parallel and by decreasing the size of the feedback capacitors C3 and C4.

A VFO tuned by a varactor

The round potentiometer adjusts the voltage on the varactor.

The advantages of varactor tuning are:

1. Varactors are mechanically stable. Assuming that the potentiometer driving your varactor is mechanically stable, then the resulting VFO will be mechanically stable. You can bang on the table with your fist and the frequency will barely warble in the receiver.

2. Varactors are more thermally stable than mechanical capacitors. When testing an exposed mechanical capacitor VFO circuit with a hair dryer, I found that the blast of hot air on the circuit board caused the frequency to soar or plunge hundreds of Hz, sometimes even a KHz of change. When my varactor VFO is given the same treatment, the frequency change is an order of magnitude less.

3. Varactors are available. Good mechanical tuning capacitors can be hard to find. In contrast, varactors can always be purchased from Digi-Key, Mouser and other companies. I recently learned that ordinary silicon diode rectifiers, like the 1N4001 and similar power rectifiers, have about 25 pF of capacitance. Two in parallel make a readily available, inexpensive, 50 pF variable capacitor. I used some in the receiver shown in Chapter 7C.

4. Varactors are tiny. Some of the ones I used are the size of a grain of sand. Soldering them to my circuit board required patience, sharp tweezers and a jeweler's loupe. However, the Motorola MV104 is packaged in a TO-92 transistor case, just like the transistors in the VFO. This particular device consists of two varactors packaged back-to-back. A varactor VFO module can be much smaller than a VFO made with a mechanical variable capacitor. Also, the varactor can be tuned by a potentiometer located at some distance away on a front panel.

5. Varactor VFOs may be tuned by phase-lock loops. Since the varactor VFO is tuned by a variable DC voltage, it can be part of a modern phase-lock loop design. A homebrew VFO doesn't have to be confined to obsolete technology.

Problems with varactors

A disadvantage of varactors is that ***the range of capacitance change is always less than a mechanical capacitor.*** Also, ***varactor-tuned VFOs are non-linear.*** However, you can turn this to your advantage. As the DC voltage is changed across the varactor, the frequency change it produces is not linear. When the voltage is first applied, the holes and electrons in the PN junction are filled in readily and decrease the capacitance rapidly. After the first big change, more and more voltage must be applied to fill in more holes and deplete the electrons in the N-type semiconductor. In other words, the wider the tuning range, the more non-linear the relationship between applied voltage and frequency. This exaggerates the tuning of the high-end frequency end of the band. For example, if the varactor is pushed to its maximum capacitance range, then 75% of the voltage tuning range might be needed to cover the upper 25% of your total frequency range.

Suppose you are primarily interested in CW operation. CW signals have little bandwidth, a few Hz, and the CW bands are often crowded. In contrast, although phone bands are sometimes crowded, the phone bands are several times wider and the phone signals themselves each cover 3 KHz. In other words, a good bandspread (small frequency change for big knob rotation) is important for the CW band and not so important for the phone band. Yes, tuning in SSB phone requires fine-tuning. However, you might find that tweaking the speech quality is more easily done with the receiver BFO knob than with the VFO tuning.

The CW portion of the band is always at the bottom of the hamband with phone at the high frequency end. The linearity problem can become an advantage by designing the VFO frequency converter in your transmitter or receiver so that, for each band, the high frequency end of the VFO range covers the low CW end of the ham band. That is, the VFO frequency should be ***subtracted*** from a higher crystal controlled converter frequency.

For example, in a transmitter, the VFO might range from 5.0 to 5.5 MHz. To transmit on 40 meters (7.00 to 7.30 MHz), the transmitter could use a 12.5 MHz crystal controlled local oscillator to cover from 7.0 to 7.5 MHz. That is, 12.5 MHz minus 5.5 MHz = 7.0 MHz. In this way, the high end of the VFO tuning covers the *LOW* end of the ham band. In contrast, if you use a low frequency crystal, 2.0 MHz (e.g., 2.0 MHz + 5.3 MHz = 7.300 MHz), the high frequency end of the VFO will cover the upper end of the phone band where bandspread isn't important. If you're confused, frequency converters are explained in detail in Chapter 11.

Or, you can use less voltage on the varactor

My newest VFO uses a Motorola type MV104 varactor. According to my capacitance meter, each side of this double device has a resting capacitance about 60 pF. You may use them in parallel or use just one. When biased with super-regulated 5 volt source from an LM336-5.0 volt Zener, it tunes from about 30 to 60 pF. It required a great deal of trial and error to produce the required 0.5 MHz tuning range with my 5 MHz VFO. All the other capacitances in the circuit had to be dramatically decreased to get the frequency high enough. Using just 5 volts to tune the varactor, instead of 10 or 12 volts, greatly diminished the capacitance tuning range. The advantage of lower voltage is that the frequency change is more linear with potentiometer rotation.

While building a 6 meter transmitter, I discovered that I could put **two MV104s in parallel**. This trick more than doubled the frequency range when used with a smaller inductor. I didn't try three MV104s in parallel because I had no more MV104s. Go for it! See Chapter 16D.

Varactor linearity

Even with low voltage tuning the varactor, frequency change is still far from linear. The good news is that 180 degrees of pot rotation out of 300 degrees varies my VFO from 5.0 to 5.5 MHz. Therefore, the first 180 degrees of knob rotation it isn't very different from my mechanically tuned capacitor VFOs. The additional 120 degrees of rotation raises the frequency from 5.5 to 5.625 MHz. I tried to make it more linear by using a conventional audio taper pot. Unfortunately, the audio taper over-corrected and the low end of the frequency span was too exaggerated. Perhaps if you use 12 volts to tune the varactor, an audio taper pot may produce a more linear scale, but I haven't tried all the possible combinations. This would be a wonderful opportunity to build a microcontroller-operated look-up table calibration system with a digital readout. I may try this, but I fear I will be unable to suppress the digital radio noise sufficiently.

Frequency offset on transmit

A transmitter VFO has a problem you may not have thought about. With an old-fashioned, wideband CW receiver, when you tune past a CW signal, you'll hear a whistle that changes from a high pitch to a low pitch or "zero beat," then rises back up to a high pitch as you continue to change the frequency. If your receiver were tuned precisely to the other guy's frequency, he would be at the "zero beat." His CW signal would have an audio pitch of zero Hertz. In other words, you wouldn't be able to hear it.

To fix this, modern transceivers automatically add a frequency offset between receive and transmit, usually 500 to 700 Hz. Also, fancy commercial transceivers don't receive the lower half of the signal unless the operator selects LSB on the front panel. In general, the lower sideband (LSB) is used on 160, 80 and 40 meters while the upper sideband, (USB) is used on 60 meters, 30 meters and above. With modern, narrow bandwidth receivers, modern hams may not even be aware that there are two sidebands. The result is that, when you answer a CQ with your homebrew VFO, you must tune from the correct direction to about 700 Hz above or below his zero beat point. Otherwise he won't even hear you. Old timers used to tune around, but modern guys don't. I believe I had this problem when I first got on the air with my homebrew rig. Few stations seemed to be able to hear me. Yet, when I did talk to someone, I got good signal reports.

VFOs for transceivers

If you build a VFO for a transceiver, the VFO will be used during both receive and transmit. As explained above, it may be useful to add a varactor tuned offset adjustment to the VFO so that you can send and receive on slightly different frequencies. To do this, add an auxiliary low capacitance varactor adjustor in parallel with the main tuning. The technology is the same as for varactor tuning, but the tuning range will be less than +/-1 KHz.

In modern SSB transceivers, CW is accomplished by transmitting a constant audio tone of approximately 700 Hz. In other words, modern transceivers never generate CW the way it was described in Chapter 6A. All voice and code transmissions are done using SSB audio tones. CW is accomplished by transmitting a fixed audio tone which is offset from where the carrier signal used to be before it was eliminated by the sideband filters. A constant audio tone transmitted by single sideband is just a sinewave with a fixed amplitude. Consequently, the resultant signal is indistinguishable from an RF oscillator generating a sinewave on the same frequency. Sideband is explained more fully in Chapter 15.

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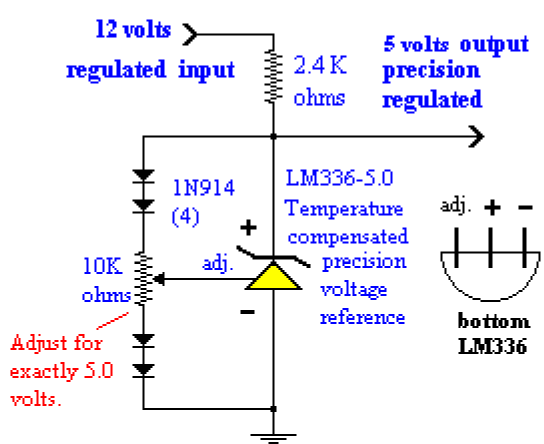
A precision power supply for the VFO

One of my early VFOs had a relentless upward drift of 200 Hz per hour. I was puzzled until I noticed that my 12 volt VFO power supply had a subtle downward drift. Ordinary voltage regulators are crude compared to temperature compensated regulator ICs. Regulators like the LM317 or LM7812 drift hundredths of a volt per minute, especially if the load is more than 100 milliamperes. A simple Zener diode regulator can easily allow one or two tenths of a volt change on the oscillator. The solution is to build a precision voltage regulator. A 12 volt regulator should be located <u>outside</u> the VFO box. So far as possible, ***anything that generates heat should be kept outside the VFO box.***

Precision Zener diodes

The trick to building a precision, temperature-compensated power supply is a precision Zener diode reference. Ordinary Zeners vary their regulation voltage with temperature. Precision Zeners are integrated circuits that behave like Zener diodes, but have temperature compensation circuitry and can be adjusted to exactly the rated voltage. The LM336–5.0 Zener diode can be adjusted with a trim pot to precisely 5.000 volts DC. It is designed to have the best temperature compensation at that exact voltage. Other than the pot and the diodes, this component is used like an ordinary Zener.



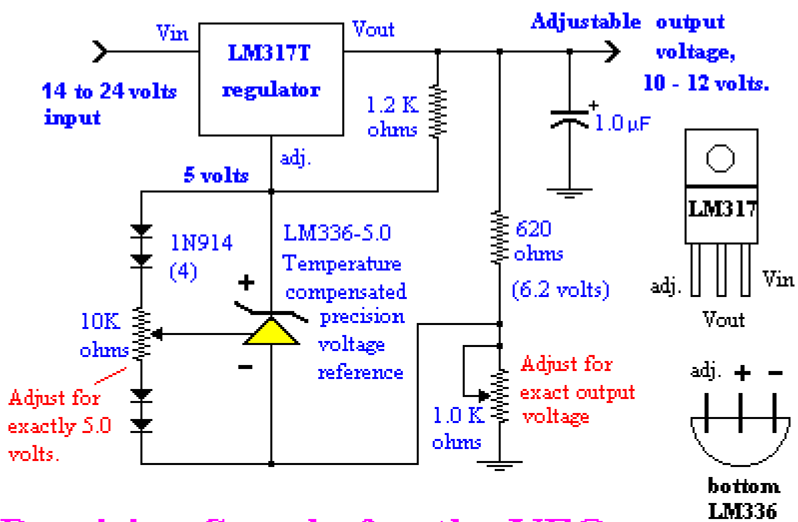
Precision 5 volt Zener

Yeah, I know. I promised I wouldn't use ICs that I couldn't build myself. I'm afraid precision regulators are beyond me. I've tried, but my attempts never exceeded the precision of the most ordinary IC voltage regulators. I did manage to build a pretty good voltage reference consisting of Zeners regulating other Zeners in a cascade in which some of the resistors were thermistors. Unfortunately, the final output was only stable at tiny voltages and tiny load currents and I couldn't successfully leverage it up to useful voltages and currents.

As you'll see shortly, this Zener circuit can supply enough current to supply the VFO oscillator directly provided that the oscillator runs on extremely low voltage and only draws a milliampere or so.

A precision 12 volt power supply

If you need more than one milliampere from your precision regulated supply for your VFO or other circuit, the precision Zener can be used as a reference voltage to control a high current, higher voltage supply. The precision voltage regulator shown below comes from the National Semiconductor Data Book for linear integrated circuits. This regulator will hold the VFO voltage constant to within about 2 millivolts. It uses a programmable LM317T regulator. (The "T" at the end identifies the TO-220 case style. There are smaller and larger versions of the LM317 available, "L" and "M" respectively. The output of the big regulator is modified with a



Precision Supply for the VFO

precision Zener reference regulator to hold the output voltage constant. The LM317 regulates the voltage across the 1.2 K ohm resistor to about 1.2 volts. The precision reference then regulates the voltage across the 620 ohm resistor to exactly 6.2 volts - that is, 1.2 volts plus 5.000 volts. Since the voltage across the 620 ohm resistor is held constant, the current passing through the 1K potentiometer is also held constant. Therefore, adjusting the 1K pot in series with the 620 ohm resistor can adjust the total voltage.

In order to maintain this high degree of precision, ***the above regulator just powers the VFO.*** When I tried to run other transmitter stages with the precision power supply, the load rose to several hundred milliamperes. Although the regulator chips were operating within specifications, the extra load ruined the millivolt precision regulation. I retrofitted my old capacitor-tuned VFO with the same precision regulator and found the frequency stability became as good as an otherwise similar varactor VFO.

A voltage doubler for battery use

If you're line powered, the regulator(s) described above will probably work just fine, ... unless there is a brown out. On the other hand, if your transmitter is battery powered, its output voltage may fall well below 12 volts as the battery discharges. One solution is to run the VFO on regulated 9 volts. That way, even with 10 volts left in the battery, the regulator will still be providing 9.000 volts. However, if your VFO uses a varactor as the tuning element, you may need at least 10 volts to get the maximum tuning range from the varactor. My first solution to this frustration was to double the unregulated battery voltage. By starting with nominally two times the battery voltage, my VFO will always have at least 12 volts. Because that particular VFO drew 10 to 20 mA DC, this DC voltage doubler did not have to be powerful. A voltage doubling charge pump for VFOs or other purpose is described at the end of the chapter.

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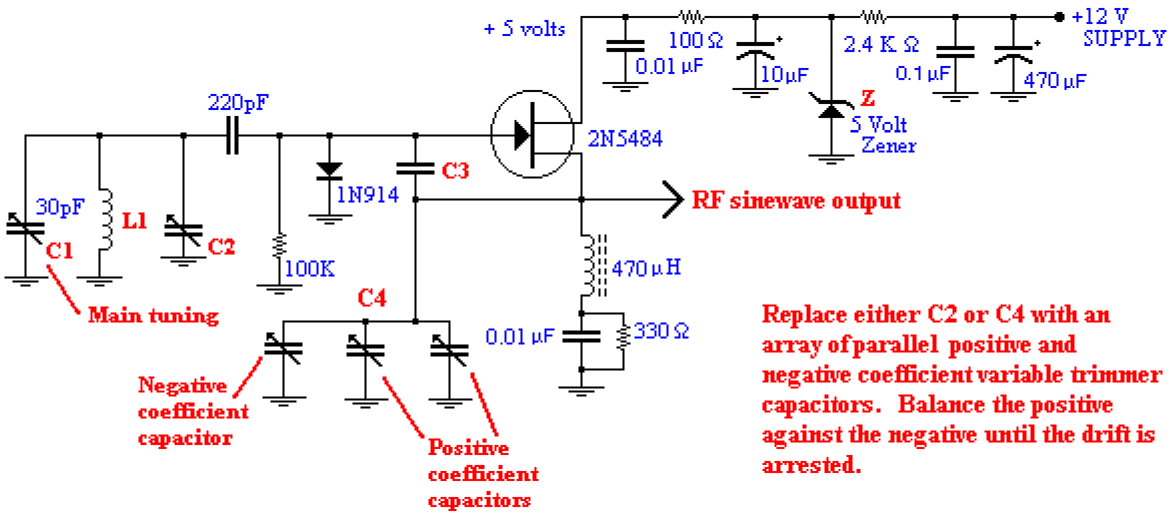
TEMPERATURE COMPENSATON

Supposedly, good VFOs can be built without temperature compensation. Personally, I've never succeeded, but don't let me be a wet blanket! Go ahead and try. Just leave room on the PC board to add compensation later.

The challenge is that most VFO parts such as variable capacitors, PC boards, etc. all have negative temperature coefficients. That is, their capacitance drops as temperature rises. The most common strategy of compensation is to substitute C2 or C4 with a capacitor that has an adjustable ***positive temperature coefficient***. Therefore by paralleling the overall oscillator capacitance with a capacitor that has an equal but opposite positive temperature coefficient, the capacitance change will be cancelled. This method uses the fewest parts and is the easiest to build. However, it's much harder to align than the other practical method which uses thermistors and a varactor for temperature control.

Positive coefficient trimmer capacitive compensation

If you look in Digi-Key, Mouser or other parts catalogs you'll occasionally find trimmer capacitors with positive temperature coefficients. These are capacitors that increase their capacitance with rising temperature. I used 20 to 40 pF variable trimmer capacitors made by Sprague-Goodman, type GCL40000. I replaced some of the fixed capacitance in the capacitive divider, C2 and C4, with two positive coefficient trimmers in parallel. ***The clever part is obtaining both the correct positive coefficient and the correct amount of positively changing capacitance. This is done by using a similar negative coefficient trimmer in parallel with the positive trimmer.*** By balancing the positive coefficient trimmer directly against an ordinary negative coefficient trimmer, you can produce a total positive coefficient value that compensates for the actual negative coefficient of the rest of your LC circuit.



POSITIVE TEMPERATURE COEFFICIENT COMPENSATION

Adjusting VFO temperature compensation

Put a 500 ohm load on the VFO output and put probes across the load for your scope and frequency counter. Check that your voltage supply is set where you want it, say 12.000 volts. It should be rock stable within a millivolt or two. If you're using a mechanical variable capacitor, set the capacitor to maximum capacitance. Now adjust the positive and negative coefficient trimmers to midscale at the desired low-end frequency of the VFO. For example, with a 5 to 5.5 MHz VFO, you would set it to 5.000 MHz (or just below). Check that you can still tune up to 5.5 MHz using the main tuning capacitance. If you can't, you may have to change C3 or fiddle with C4 or C2. Remember that C2 can also be a positive or negative coefficient trimmer, depending on what you need. Or, if you have trouble reaching a high enough frequency, you could leave C2 out entirely and adjust the frequency range with C3 and C4.

Now put the lid on the VFO box but don't screw it down. Watch the frequency drift on your frequency counter. You will almost certainly see it ***drift relentlessly up or down.*** If it is going down, assume this is caused by increasing temperature in the box. Turn a positive trimmer to *LESS* capacitance, then adjust a negative trimmer to restore the frequency back to where you started. Repeat this again and again until the drift direction reverses. Now it should be going relentlessly *UP*. Now take off just a bit of the negative trimmer until the drift comes to a halt. When you get them balanced well, the frequency will still change, but now it will ***wander up and down but soon return to the same frequency***. In other words, the frequency will no longer march continuously in the same direction. When you get to this point, you have done as well as you can with your present set of components. With luck, during any given minute it won't wander up or down more than 5 Hz per minute.

I had not used my capacitively compensated VFO for years. But when I did, the VFO was drifting downward at 60 Hz a minute. I removed it from the transmitter and spent a morning trying to realign it. Although I could adjust it to stop the drift, I couldn't get it to line up with the frequency span that I needed. Also, the adjustment on the trimmer capacitor was extremely critical. In frustration I finally tore out the capacitive compensation and replaced it with thermistor/varactor compensation described below.

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Thermistor temperature compensation

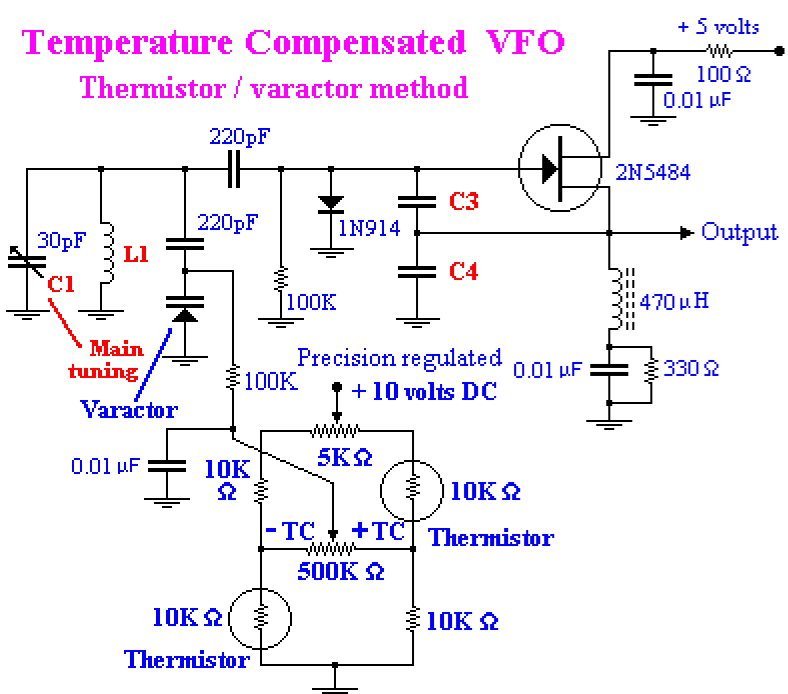
You may find that your positive trimmer capacitance compensator just doesn't give you enough positive compensation to be effective or it's simply too hard to adjust. A ***thermistor*** compensation circuit may be just what you need. I've had good results with the ARRL handbook circuit below:

A VFO also needs regulated power supplies

I used a precision Zener reference regulator to hold the +5 volt supply voltage constant. The LM317 regulates the voltage across the 1.2 K ohm resistor to about 1.2 volts. The precision reference then regulates the voltage across the 620 ohm resistor to exactly 6.2 volts - that is, 1.2 volts plus 5.000 volts. Since the voltage across the 620 ohm resistor is held constant, the current passing through the 1K potentiometer is also held constant. Therefore, adjusting the 1K pot can adjust the total voltage.

In order to maintain this high degree of precision, ***the regulator shown below just powers the VFO.*** When I tried to run other transmitter stages with the precision power supply, the load rose to several hundred milliamperes. Although the regulator chips were operating within specifications, the extra load ruined the millivolt precision regulation. I retrofitted my old capacitor-tuned VFO with the same precision regulator and found the frequency stability became as good as an otherwise similar varactor VFO.

The temperature compensator has 2 thermistors in a bridge circuit with a thermistor on each side of the bridge. The entire circuit is powered by a precision regulated supply, 5 or 10 volts. By adjusting the 5K and 500K trimmer pots at the top and middle, the degree and direction of the compensation can be selected. Tuning the 500K pot to the right selects more positive compensation. Tuning to the left selects less positive compensation or possibly even negative compensation. If you need more capacitance, you can always parallel two (or more) varactors.



Adjusting the thermistor temperature compensation

The trial and error thermistor compensation adjustment is much the same as with the capacitance method. Once you adjust the compensation so that it drifts less than, say 50 Hz, set your counter to a setting that will read out individual Hertz, such as 5,000,000 Hz. I like to write down a column of readings as my counter produces them every ten seconds. At the top of each 3 minute trial I record the settings, such as "left pot full clockwise, right pot 1/2 range." That way, I won't be making random trials with no record of what setting worked best. If this simple strategy fails, resort to a more methodical method:

First, adjust your precision regulator (LM336) to precisely 5.00 volts. That's the voltage at which the manufacturer says the internal regulator temperature compensation works the best. Next check out the extreme settings of the trim pots. What does the frequency drift do at the extremes? Hopefully you can access one end or the other of the upper 5K pot. It should range from, say 8 volts up to 10 volts. Next, check out the extremes of the lower 500K pot. Look at the voltage at the pot wiper, the end of the 100K resistor. This reading is a little tricky because, if the compensation is working right, the voltage you read will be constantly changing slightly. But you can get the general idea of effects of extremes which are between, say 3.7 and 5.3 volts. Set the upper pot first, the 5K, then trim the result with the 500K.

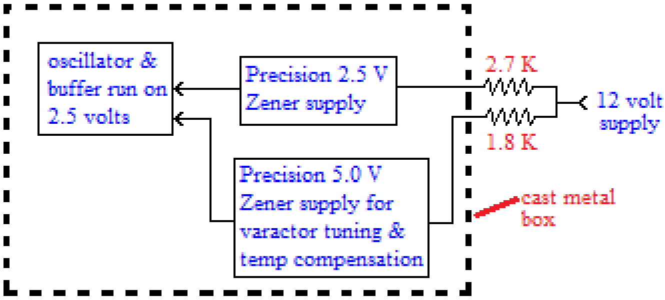
Remember that hams only transmit for a minute or two at a time, so in a transmitter there is little reason to worry about stability after 5 minutes. In a receiver, the oscillator may be left running and the initial frequency drift is not important. Concentrate on stability during the first 2 minutes. My VFOs all tended to drop quickly in frequency during the first half minute, then they stabilized completely after 2 or 3 minutes. You'll find as you repeat the experiment with the same settings and the lid on the box, you'll sometimes get a different result. Hopefully the change not very different. This process can be quite frustrating! Take a break and try again later if your blood pressure is rising.

Sometimes I could adjust it so that it stabilized well, but I still had an initial drop of 40 or 50 Hertz. One trick I discovered was that I could also adjust the trimmer pot on the precision Zener that runs the oscillator. Yes, the data sheet says it's supposed to be set at exactly the rated voltage, 5.000 volts. However, I found I could set the voltage high and eliminate the initial drop in frequency. For example, instead of setting a trimmer to 5.000, set it to say 5.300 and see how the oscillator responds. Experiment!

Separate regulation for the VFO oscillator

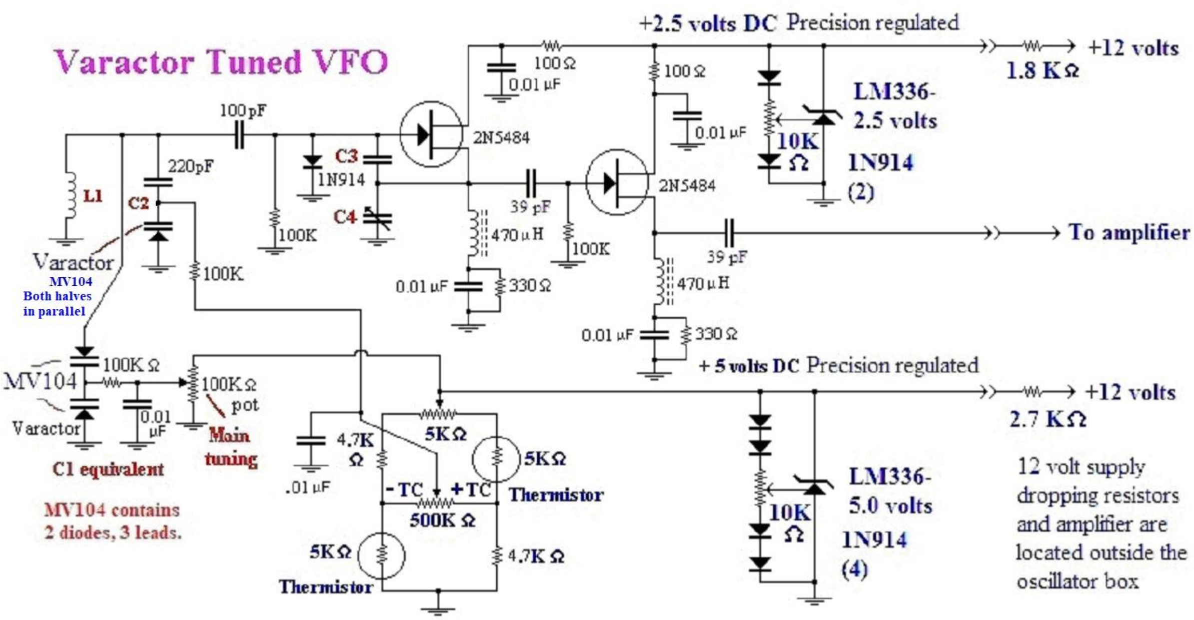
If the entire VFO is consuming more than about 10 mA, you can limit the temperature change inside the box by powering the oscillator and buffer inside the VFO box using a 2.5 volt Zener, instead of 5 volts. Since the oscillator and buffer together only draw about a milliampere, they can be powered by connecting it across the Zener reference diode. No auxiliary linear supply regulator or amplifying transistor is needed. In addition, the dropping resistors between the 12 volt source and Zeners can also be located outside the oscillator box, eliminating even those small sources of heat. The power supply needed for the temperature compensation varactor is also tiny and can be obtained directly from a 5 volt precision Zener.

Tuning the varactor with a 5 volt supply means that the varactor is operating at the low end of its tuning range. The low end is more linear than the high end of the varactor range. At the high end big voltage changes are needed to make small changes in varactor capacitance.

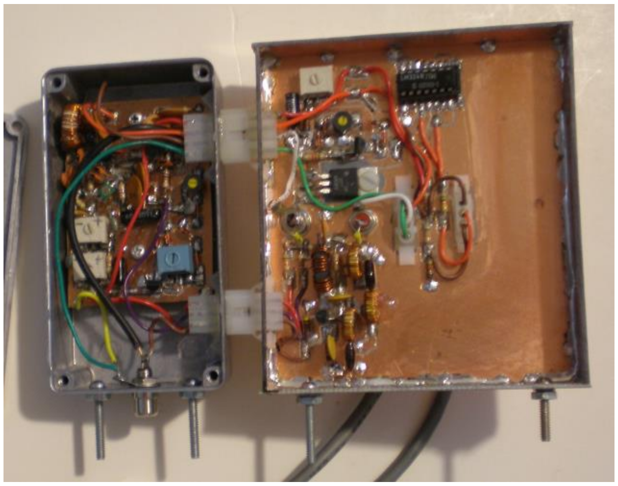


Varactor tuned and stabilized VFO

The block diagram for my latest VFO oscillator and buffer is shown above. The oscillator and buffer are powered by a 2.5 volt precision Zener, LM336-2.5 volt. This different part number is just like the 5 volt version, but produces 2.5 volts instead. The oscillator and buffer are housed in a cast metal box. Both stages run on about 1 milliampere. The varactor tuning is powered by a separate 5 volt precision Zener, LM336-5.0. Both Zeners are contained in the cast metal enclosure.



The varactor tuned VFO oscillator is shown above.



The varactor tuned and thermistor temperature compensated VFO

The temperature compensation circuit is on the lower left of the cast metal box and includes the two white square trim pots. Oscillator, buffer, temperature compensation and 2.5 volt and 5 volt Zener diode supplies are all enclosed in the cast metal box. The final amplifier which runs on 12 volts and an additional power supply are on the right. The tuning potentiometer is connected to the front panel with the gray cable. The second gray cable is an (optional) tuning band-spread pot.

The printed circuit box on the right houses the "high power" final amplifier that runs on the regular 12 volt supply. The integrated circuit at the top right is an operational amplifier wired as a voltage follower for a vernier adjustment potentiometer in parallel with the main tuning potentiometer. Because the vernier adjustment potentiometer can effect the VFO drift, the operational amplifier has yet another precision Zener supply, this time with a regulator and designed for 9 volts. In spite of all my former noisy digital experience, I am still hoping to develop a digital frequency display with this operational amplifier. That is why the right hand side of the auxiliary box is still nearly empty. Hope springs eternal!

Molex connectors

Notice that the VFO oscillator box and its amplifier are connected with white plastic "Molex" connectors. These cheap and extremely versatile connectors are convenient any time you need to connect more than one unshielded wire between modules. The connector pairs are available in many different styles, sizes and numbers of conductors per connector. 1, 2, 3, 4, 6, 8, and 12 conductor pairs are available and probably more versions as well. Usually Molexes are used to connect one multiple wire cable to another, but in the example above, I am directly connecting two modules.

Molex connectors are really two connectors in one. The plastic part is a "frame" that holds the small metal connectors. The outer plastic "frames" come in female and male parts which clip together. A bump on the male part engages the female portion. The female half has a plastic tab which bends over the bump and secures it. Actually these clamps work much too well and are hard to pull apart. I usually use my pocket knife to carve the bump off the male half so the connectors can be plugged and unplugged without resorting to violence. Some versions have outer tabs that allow them to clip onto the edges of holes in a chassis, as in the VFO above. If you don't need the outer tabs, simply snip them off with your diagonal cutter.

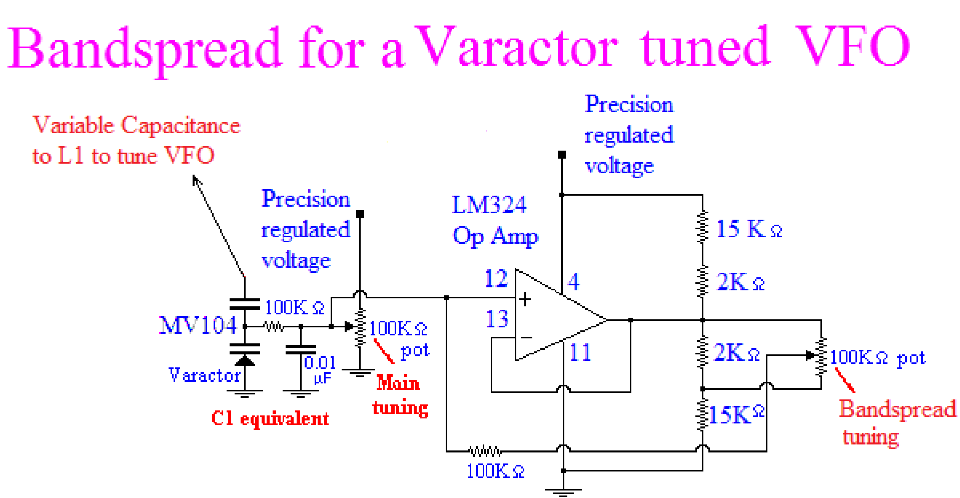
The tiny metal conductor pins are also male and female. The male or female pins are inserted into male or female outer frames and click in place. I usually use Molex connectors made for the 0.062" pins. Larger Molex connectors use 0.093" pins which carry more current. Even larger size Molex connectors can carry heavy currents, tens of amperes. You don't need to have metal pins in every plastic casing hole. Male pins can be used in female outer frames and vice versa. So, if you have several cables to connect, you can mix up the combinations of male, female and holes, so that numerous pairs of connectors cannot be interchanged accidentally.

Mated pairs of male and female pins can also be used as a tiny, stand-alone connectors without the outer plastic frame. To insulate the pieces, I carefully shrink small diameter shrink tubing over the pins. Shrink tubing is available in kits of short pieces in a rainbow of colors. This provides a way to mark single pin connections so they will not be confused. The 2 meter transmitter photograph in Chapter 16B shows many of these brightly colored single pin connectors.

A similar varactor tuned, temperature compensated VFO

Chapter 16D has a comparable VFO that was built for a 6 meter SSB transmitter. The VFO tuning range was increased to 1.2 MHz without sacrificing stability. This was accomplished by using two MV104 varactors in parallel. It's equipped with both thermistor temperature compensation and precision supplies for both the oscillator and varactor tuning. The bandspread function is accomplished with a 1 megohm pot, isolated from the supply and ground with 470K resistors. This avoids having the bandspread radically change the frequency at the grounded end or supply end of the bandspread pot travel.

Additional bandspread for varactor tuned VFOs



A circuit to increase the bandspread frequency control of a tuning potentiometer is shown above. The idea is to introduce a small positive or negative offset voltage into the coarse frequency tuning. This makes it easier to tune in SSB signals or zero-beat another station more accurately. The tricky part is that the reference for the offset voltage must move with the wiper contact of the main tuning pot. The operational amplifier is wired as a voltage follower so that it can track the wiper without any significant effect on the frequency. The bandspread pot then provides a variable offset from that level. So far, I haven't noticed that the bandspread introduces any frequency drift. It tracks SSB stations for minutes on end without any change in the speaker's voice.

Why isn't the top of the bandspread pot connected between the upper 2K and 15K resistors? Because when you wire it that way, the frequency goes up in both directions when the bandspread pot is adjusted off center. I know! I didn't predict that either! This way, the bandspread pot goes up when rotated in one direction and down in the other. You may want to change the resistor values to achieve a different KHz range of bandspread. Mine has a range of about 1 KHz. The easiest change is to adjust the 100K resistance between the bandspread pot and the main tuning pot.

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Using precision Zener diode regulators for their temperature compensation

LM336 regulators compensate for temperature changes automatically in order to stabilize the chip output voltage. Eventually I discovered that LM336 regulators can compensate for temperature changes in the entire oscillator/buffer circuit. This in turn stabilizes the frequency. We must still thermally isolate the oscillator and buffer from the rest of the transmitter. You begin by setting the output voltage to the regulator design voltages, 2.500 or 5.000 volts DC. When you put the lid on the little VFO box, the frequency will establish an obvious pattern of drift. The frequency will continuously change up or down. Remove the cast metal lid and tweak the adjustment pot of one of the regulators, perhaps up to 2.550 Volts. Replace the lid and watch the frequency. Now maybe it is drifting downward. Next try 2.450 Volts. If you're lucky, now it will drift upward. By trial and error you can zero in on one consistent frequency. It will never be entirely unchanging but will wander around a single frequency. If you are using one or more additional LM336-5.0 Zeners to bias the varactor, you may to have adjust those as well.

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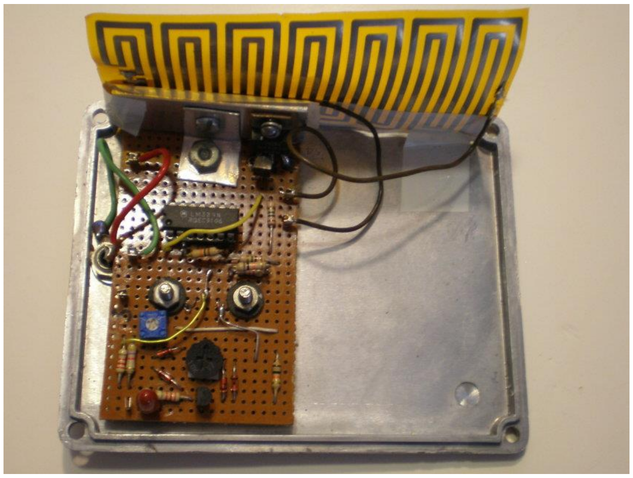
Thermostat regulated heater

The last and least practical way to achieve temperature compensation is the brute force method. In this scheme the temperature is held constant by heating the VFO and regulating the temperature with a thermostat. I built such a device inside the lid of a cast metal box. The heater used a resistive heater element printed on a Kapton sheet and a thermistor-controlled temperature regulation feedback system. The good news was that it regulated the box temperature to within 0.1 degree Fahrenheit. The bad news was that it took the temperature at least 30 minutes to stabilize and, when installed in the transmitter, the regulator was trying to heat the whole transmitter and perhaps the entire room. In other words, a heated VFO box must have extensive thermal insulation in order to be practical. I gave up on this idea.



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A DC voltage doubler

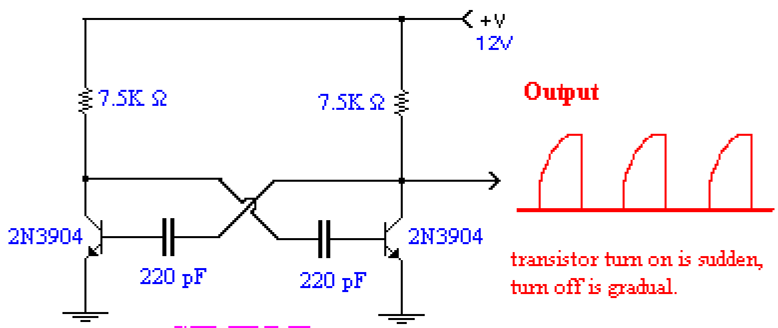
Square wave generation

Suppose you wish to build a 12 volt precision regulated power supply for a varactor controlled VFO. If you are using a storage battery to power your station, the battery voltage may drop as low as 11 volts, and you will need to increase the battery voltage. A related problem is that, if you are battery powered and using your QRP with a 50 or 100 watt linear amplifier, the battery voltage may rise and fall slightly as you send CW. As the voltage drops, the VFO may momentarily shift frequency and make a chirping sound. In other words, your signal report might be "UR RST 599C," where "C" means chirp. In the old days, it was common to hear a report like "RST 599X," in which the "X" meant, "It sounds like crystal (Xtal) control." That is, your signal ***isn't*** drifting. In the modern world, no one drifts except us homebrew guys. I haven't heard an "X" in years.

As you learned in Chapter 6A, we use large capacitors and isolation resistors to prevent a sudden drop in VFO supply voltage. However with high power drawn from a battery, the VFO may drop suddenly at the end of a CW "dash," resulting in a chirp. In other words, the tone of CW drops like a singing bird. Another way to fight chirping is to run the VFO supply input on a much higher voltage, say 22 volts instead of 12 volts. With that much extra voltage the VFO supply can drop 10 volts before it ever arrives at 12 volts.

When we wish to raise a DC voltage, it is necessary to use the existing DC supply to generate a source of AC voltage. For example, the AC voltage could be applied to a transformer to produce as high an AC voltage as you need. The high AC voltage would then be rectified back into DC at the required high voltage. Instead of using a transformer, the voltage doubler described below uses a capacitive ***charge pump*** to raise the voltage. As you'll see, this technique is a specialized kind of rectification.

The first task is to convert the DC supply to square wave pulses. There are many ways to generate square waves using integrated circuits. For example, I used an operational amplifier IC to generate the dots in the electronic bug in Chapter 9. You may use an IC if you like, but you might enjoy doing it the hard way. As usual, if you're new to electronics, you'll learn some interesting concepts.



SIMPLE ASTABLE MULTIVIBRATOR

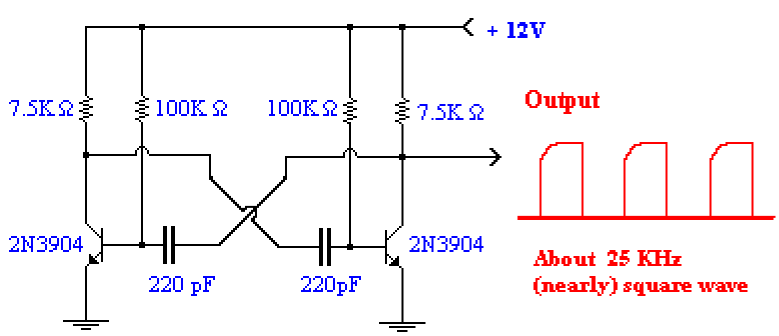
A simplified ***astable multivibrator*** oscillator is shown to the left. As you can see, this circuit consists of two grounded emitter amplifiers wired so that any change on the collector of one transistor is immediately coupled to the base of the other. Let's assume that the capacitor on the left is charged to a low voltage, say 1 volt. The capacitor on the right is charged to nearly 12 volts. The capacitor on the left is charging toward 12 volts through the 7.5 K resistor on the right. As the positive charge flows out of the capacitor and into the base, the left transistor turns on. This pulls its collector and its respective capacitor toward ground.

Since the voltage across the capacitor on the right can't change instantly, the voltage on the right base is pushed downward to roughly –12 volts. This extreme negative voltage turns off the right hand transistor. The right hand capacitor with its –12 volts will discharge toward zero volts since there is now no source of voltage to maintain negative 12 volts. This discharge takes a significant length of time because the current must bleed into it through the 7.5 K ohm resistor. Eventually, the voltage on the right transistor's base rises above +0.6 volts, which will turn that transistor back on. When the right transistor turns on, it pushes the left hand capacitor back down to –12 volts turning off the left transistor.

A practical multivibrator

The simplified multivibrator described above oscillates OK, but it doesn't always start spontaneously. In fact, you will find that it only runs at a specific range of supply voltage and must be turned on abruptly. If you turn up the supply voltage gradually, the multivibrator remains stable with one or both sides turned off and the oscillation never begins.

The unreliability of the simple multivibrator can be fixed by biasing the transistors partly *ON* with the 100K ohm resistors. These resistors insure that the capacitors will always be charging or discharging. Now the circuit will generate square waves even with very low voltages. When the power supply voltage is turned up slowly, the oscillation will always start. Also, the *ON* state of each transistor is maintained longer and a better square wave results.



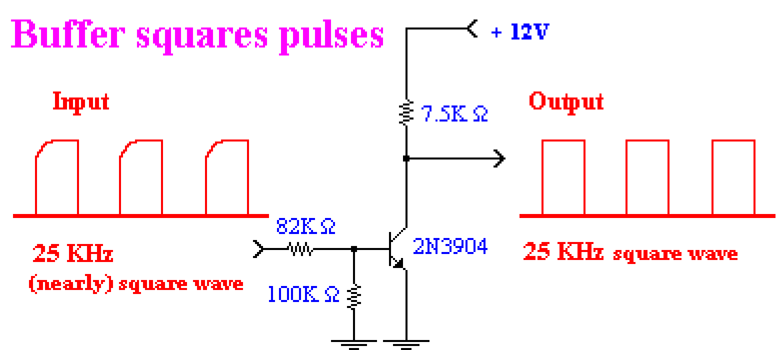
ASTABLE MULTIVIBRATOR

Bistable multivibrators are RAM flip-flops

This is off the subject, but suppose that the two capacitors in the above circuit were replaced with high resistance resistors. Since there would be no reactance to charge or discharge, the circuit would "lock up" with one transistor *ON* and the other *OFF*. This is called a ***stable-*** or ***bistable-multivibrator.*** If a pulse is introduced to one transistor or the other, the circuit can be made to "flip-flop" to the opposite stable state in which the *OFF* transistor turns *ON* and the *ON* transistor turns *OFF*. The ***flip-flop*** circuit is the basis of static RAM memory (SRAM). One flip-flop can store one bit of information. So long as the supply voltage is applied, the circuit will "remember" one bit of information indefinitely. Or, it will remember it until another pulse comes along and resets it to the opposite state. In an integrated circuit SRAM there are literally millions of flip-flops printed on a chip storing megabits of information.

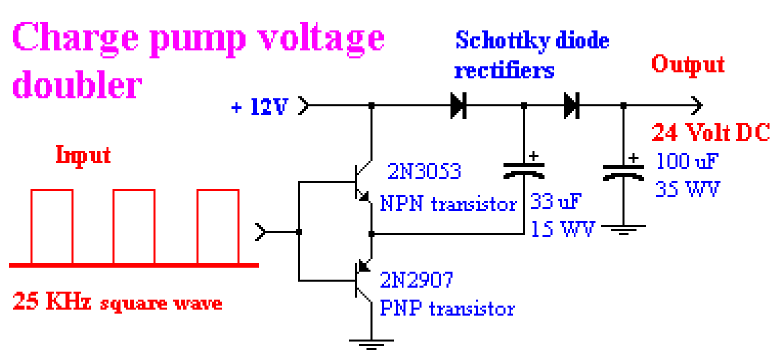
Squaring up the low power square wave to drive a doubler charge pump

Now that we have a low-power, square-wave voltage, we need to clean up the waveform and amplify it so that we can produce about 30 mA squarewave AC for our VFO power supply. This is done with a simple buffer amplifier to make it square. A square waveform is important because the less time that the circuit spends "half turned on," the more efficient the power supply will be.



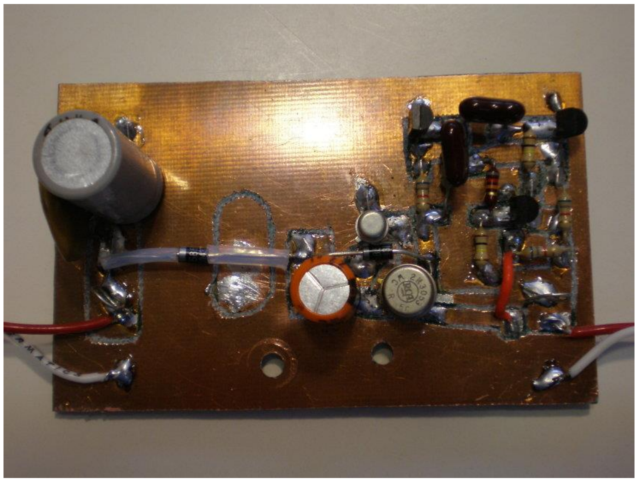
This square wave buffer is just a high gain voltage amplifier. During the sloping, rising input voltage, the upward slope of this voltage is exaggerated by 10 or 20 times. This diminishes the rise time until the rise time becomes negligible.

Diode voltage doubler



How can we "double" DC voltage using diodes? The idea is to repeatedly charge the 33 µF capacitor to +12 volts as though that capacitor were a rechargeable battery. Then the capacitor is switched out of its "charging mode" and added like a battery on top of the existing 12 volt supply. In other words, 12 volts plus 12 more volts equals 24 volts. This pulsing, 24 volt signal then charges up the large 100 µF storage capacitor on the right to 24 volts. Provided the current drawn from the 24 volts supply is small, the capacitor on the right can maintain a relatively constant voltage approaching 24 volts.

As shown above, the PNP and NPN transistors work together to pull the left hand capacitor up and push it down. When the PNP transistor is turned on, the bottom end of the capacitor is connected to ground. In this condition the diode on the left charges the 33 µfd capacitor up to 12 volts. When the PNP turns off and the NPN turns on, the bottom end of the capacitor is suddenly shoved "up" and tied to the 12 volt supply line. Since the top of the capacitor is suddenly 12 volts higher than the supply line, the diode on the left is back-biased and can no longer charge it. Instead, the diode on the right is now forward biased and will discharge the 12 volts into the 100 µfd storage capacitor on the right. The capacitor on the right of the schematic charges toward 24 volts thereby creating twice the original voltage. Below is a photo of the 12 volt voltage doubler. The output is on the left. It can handle at least 30 milliamperes load current without appreciable heating on the switching transistors. As you can see, the PC board shows the scars of an earlier, simpler approach to the voltage sag problem that didn't work. You may substitute a 2N2222 with a metal case for the larger 2N3053 that I used.



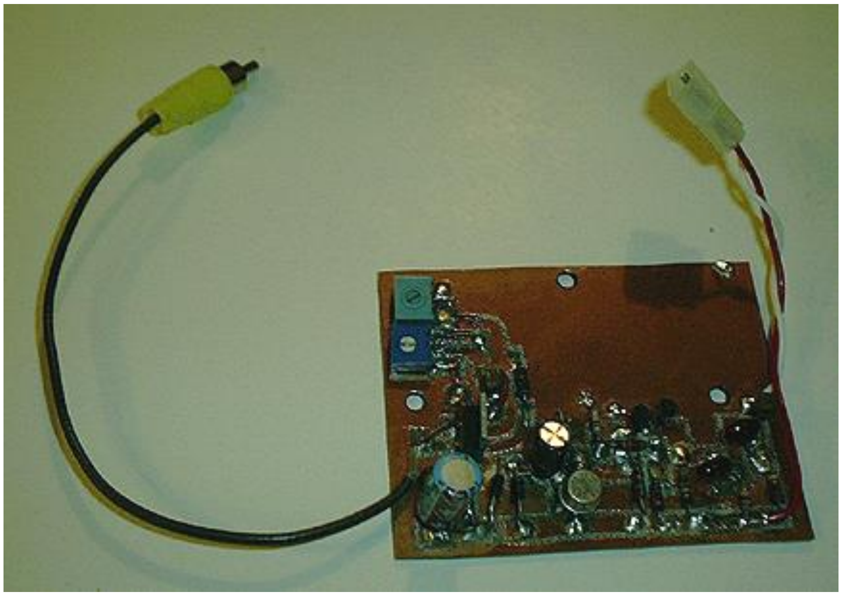
Complementary transistors in action

In Chapter 4 I mentioned that it was often convenient to have transistors that work with opposite polarities. As the drive to one transistor turns it on, the same polarity turns its complement transistor off. The output is taken off the emitters. In effect, the complementary transistors connect the output back and forth between ground and the 12 volt supply without any resistors becoming hot and wasting energy.

By the way, the logic circuits in your personal computer are almost entirely implemented with integrated circuits made from **C**omplementary N-channel and P-channel **MOS**FET transistors. These ICs are called ***CMOS***. By avoiding using resistor loads on the FET drains, heating is minimized and switching speed is maximized.

Use Schottky rectifiers for best efficiency

Now we have lots of extra voltage, even when the battery supplying the transmitter is nearly exhausted, so there will always be plenty of voltage for the precision regulator to generate 12.000 volts. The supply works best if the two diodes in the voltage doubler are power Schottky diodes. These rectifier diodes only waste about 0.2 volts per diode when conducting current. The down side of Schottky rectifiers is that they can usually only tolerate about 30 volts maximum, but that's plenty for this application.



A VFO power supply board. It has a widely varying battery voltage input but delivers a precision regulated 12 volts output.

Drift and chirp

Eventually, after you have successfully used your VFO for years, someone may complain about your drifting signal. Not surprisingly, this will first occur during a *L-O-N-G* conversation of 40 minutes or more. When you check out your VFO, sure enough, it is drifting up or down at 20 Hz/minute or more. After an hour, even a 20 Hz drift begins to be obvious. Clearly you need to repeat the alignment process and return the oscillator to stability.

"Chirp" is shift in VFO or crystal oscillator frequency that causes the musical tone of the CW to change during dots and dashes. In general, the more power your transmitter draws from the power source, such as batteries, the more likely chirp becomes. Chirp can happen even though you have done everything you can to isolate and filter the supply for your VFO. In my experience, transistorized QRPs are quite unlikely to chirp. However, when you feed them into a high power amplifier, the high current surges may cause the supply voltage to hop up and down with the Morse code. Because you have done a good job with the VFO supply filters and isolation, the chirp first occurs at the *END* of long dashes when the isolation begins to fail. Consequently, one way to avoid chirp is to send really fast! Better ideas are to make sure the antenna is properly tuned and that the power supply contacts are clean and solid. This is especially important with a station that runs on deep-discharge batteries like mine. The positive terminals of lead-acid batteries tend to corrode first. This causes voltage drop when surges of current pass through the oxide and salt-caked terminals.

In conclusion,

Low oscillator voltage, precision voltage regulation, temperature compensation and careful adjustment can produce a homebuilt VFO that doesn't drift like a homebuilt. When you get on the air and describe your rig as "all homebrew," the stations you work will (sometimes) shower you with praise. Enjoy every compliment. If you needed as many prototypes as I did to develop a reasonably good VFO, you deserve kudos. Actually, the best complements I've had were when I yacked with guys for an hour without any complaints about my drift.